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Airborne laser scanning for riverbank erosion assessment

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Abstract

Worldwide, rivers and streams are negatively impacted by sedimentation. However, there are few broad scale techniques for quantifying the sources of sediment, i.e. upland vs. river bank erosion. This research was designed to evaluate the use of airborne LIDAR for characterizing sediment and phosphorus contributions from river bank erosion. The evaluation was done on the main stem of the Blue Earth River in southern Minnesota. Detailed topographic data were collected on an annual basis in April 2001 and 2002 over a 56 km length of the river with a helicopter mounted Topeye laser system. The raw database included X, Y, Z coordinates of laser returns sampled from the river valley with a density of 1–3.3 elevations per m^2. Uniform 1 m bare earth digital elevation models were constructed by stripping vegetation laser returns and interpolation. The two models were differenced to determine volume change over time, which was then converted to mass wasting by multiplying volume change with bulk density. Mass wasting rates were further converted to sediment load based on percentage of transportable material in the bank strata. The average difference between LIDAR measured elevations and RTK GPS surveyed elevations on 5 highway bridge surfaces was 2.5 and 8.8 cm for the 2001 and 2002 scans, respectively. The elevation errors were quasi-normally distributed with standard deviation of 6.7 and 6.1 cm for 2001 and 2002, respectively. No elevation or planimetric corrections were made to the laser data before calculating mass wasting rates because it was not possible to determine the source of error or if it was uniform within and between scans. The mass wasting estimate from the LIDAR surveys varied from 23% to 56% of the sediment mass transported past the downstream gauging station depending on the range of textural material that was entrained once in the river. These estimates are in the range of values reported in the literature. Total P contribution due to bank erosion from the river reach was estimated to be 201 t/yr.

Keywords: Sediment pollution; Laser altimetry; LIDAR; Bank erosion

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1. Introduction

Bank erosion contribution to suspended sediment load varies widely from 17% to 93% for rivers studied in England, Europe and North America (Sekely, Mulla, & Bauer, 2002). Such a wide range in values is due to many factors including differences in climate, topography, geology, soils, and land management. The National Water Quality Inventory report (USEPA, 2000) indicates 12% of assessed rivers and streams in the U.S. are impacted negatively by sedimentation. Negative impacts of siltation include suffocation of fish eggs, decreased light penetration for photosynthesis, decreased aesthetic value for recreational uses, and added cost of water treatment.

Agriculture is implicated as the major source for sediment pollution in many rivers. Phosphorus adsorbed to soil particles is often delivered with sediment further contributing to water quality degradation through eutrophication (Sharpley et al., 2003). However, because of their diffuse nature, reductions in sediment and phosphorus are difficult to achieve, but are typically attempted through implementation of conservation practices. Conservation tillage and grassed waterways as well as buffer strips at field edges can reduce sediment and phosphorus transport to

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surface waters (Gupta & Singh, 1996; Randall et al., 1996). However, sediment and phosphorus sources in agricultural landscapes include both bare fields as well as riverbanks in dynamic fluvial systems. Therefore, determining the proportion of sediment and phosphorus delivered from either of these sources is a difficult, yet important task for cost effective implementation of conservation measures, or engineering solutions for bank erosion.

Airborne laser altimetry has been used in numerous topographic and land use change detection studies (Huising & Gomes Pereira, 1998; Irish & Lillycrop, 1999; Krabill et al., 1999; Murakami et al., 1999; Sallenger et al., 1999). Laser altimetry has also been used for gully erosion estimates (Jackson et al., 1988; Ritchie et al., 1994), earthquake fault mapping (Harding & Berghoff, 2000; Hudnut et al., 2002), and to map riverbank elevations for flood management (Pereira & Wicherson, 1999).

As the aircraft moves along a predetermined flight line the LIDAR system sends many thousands of laser pulses to the ground each second in a scanning pattern centered on the flight line. Up to five echoes from each laser pulse are received by the sensor to compute elevations based on laser travel times. Typically, the first returned pulse is from the top of the vegetation canopy while the last is usually the ground. In situations where the last echo return is not the ground, filtering must be employed to remove vegetation elevation data if interest is purely in the bare earth elevation (Ritchie et al., 1994). Typically, the high density of data from combinations of multiple passes allows spatial averaging of elevations without loss of systematic variation in the landscape surface elevation (Ritchie et al., 1994). An Inertial Measurement System (IMU) is used to measure aircraft attitude during the flight which is used to correct for errors due to roll, pitch and yaw. Most IMU's have angular resolutions of approximately 0.01 degree (Fowler, 2000) which can induce error up to 2.5 cm vertical and 7.4 cm horizontal at 20 degree scan angle and 375 m flight altitude. This error represents a large fraction of the LIDAR errors and cannot be easily removed. Resulting data resolution depends on aircraft elevation and speed as well as laser pulse rate, scan width, scan rate, and vegetation cover. Data collection in the fall or winter during leaf-off conditions optimizes sampling density and accuracy of bare earth measurements.

The 6294 km^2 Blue Earth River watershed in south central Minnesota is a good example of a landscape where non-point source sediment and phosphorus pollution are prevalent, but difficult to apportion between upland and stream bank erosion. The 160 km long Blue Earth River has a mean discharge of 37 m^3/s with maximum flood flow of 1699 m^3/s and average gradient less than 0.6 m/km. The Blue Earth River is a major tributary of the Minnesota River and contributes about 55% of the sediment load carried by the Minnesota River at Mankato, MN (Payne, 1994; WRC, 2004). The Minnesota Pollution Control Agency (MPCA, 1985) stated that a 40% reduction in sediment load carried by the Minnesota River would be required to meet federal water quality standards and beneficial use criteria. Thus far, the cause of this pollution has been blamed on agricultural practices in relatively flat upland areas of the watershed. Therefore, the strategy for controlling these pollutants has also focused on implementing agricultural practices that limit delivery of sediments and nutrients to the river (Randall et al., 1996). However, this strategy may be ineffective since it is not clear what proportion of the sediment and nutrient pollution in the Minnesota River is from upland erosion or stream bank erosion.

Objectives of the study were to 1) evaluate the capabilities and limitations of LIDAR remote sensing for river bank erosion, 2) quantify mass wasting and phosphorus inputs along a 56 km length of the Blue Earth River, and 3) estimate the proportion of total annual suspended sediment and phosphorus loads due to bank erosion.

2. Methods

Research focused on a reach of the Blue Earth River between Amboy, MN and the confluence of the Blue Earth and the Wantonwan rivers (56 km; Fig. 1) that contained 10 minor, 30 moderate and 15 severely eroded sites according to Bauer (1998). Severely eroded sites were classified as greater than 3 m high (Fig. 2). In this stretch of the river, five county highway bridges were used as ground reference control for the LIDAR scans.

2.1. Scan specifications

LIDAR scans were conducted on April 23–24, 2001 and April 26–28, 2002 with a Saab Topeye helicopter mounted laser range finding system at about 375 m above ground level. Laser pulse rate was 7 kHz measuring between 1 and 3.3 elevations per m^2, with foot print diameters of 0.16 m. Scan width was 273 m. A ground control station near Garden City (designated SCHOEB; UTM: 4880562.343N, 407248.996E) was used for differential correction in both 2001 and 2002. Additionally a second pair of ground control stations was established for the 2002 survey near Vernon Center, MN (UTM: 4868658.493N, 406207.778E; and 4868658.526N, 406229.837E).

2.2. Fieldwork and laboratory analysis

Twelve samples were collected from six exposed riverbanks representing typical strata and textures in bank materials. The taller stream banks were primarily composed of glacial till and glacial lake sediments (Bauer, 1998), while shorter banks were composed of river alluvium. Replicates of each sample were characterized for bulk density using the clod method (Blake & Hartge, 1986) whereas textural analysis was made using the hydrometer method (Gee & Bauder 1986). Averages of bulk density and

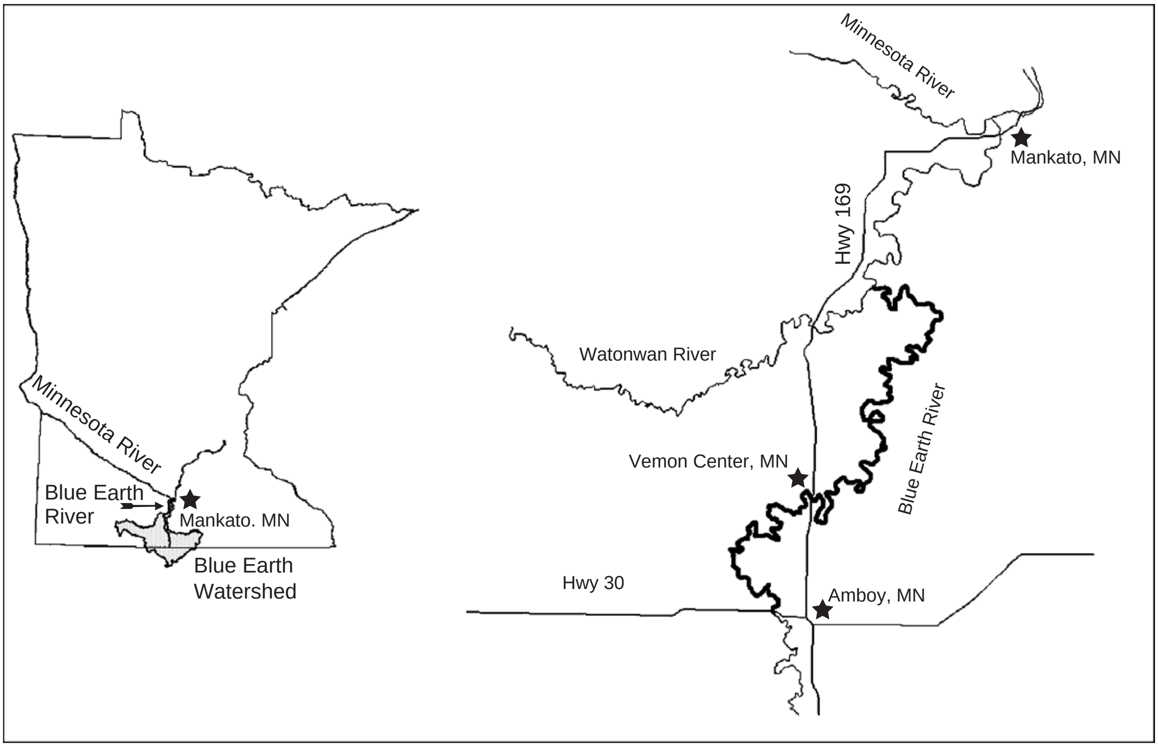

Fig. 1. The study area was a 56 km section of the Blue Earth River (thick line in the figure on right) scanned with a laser altimeter in 2001 and 2002. This reach of river is between the confluence of the Blue Earth and Watonwan Rivers and the Highway 30 Bridge near Amboy, MN.

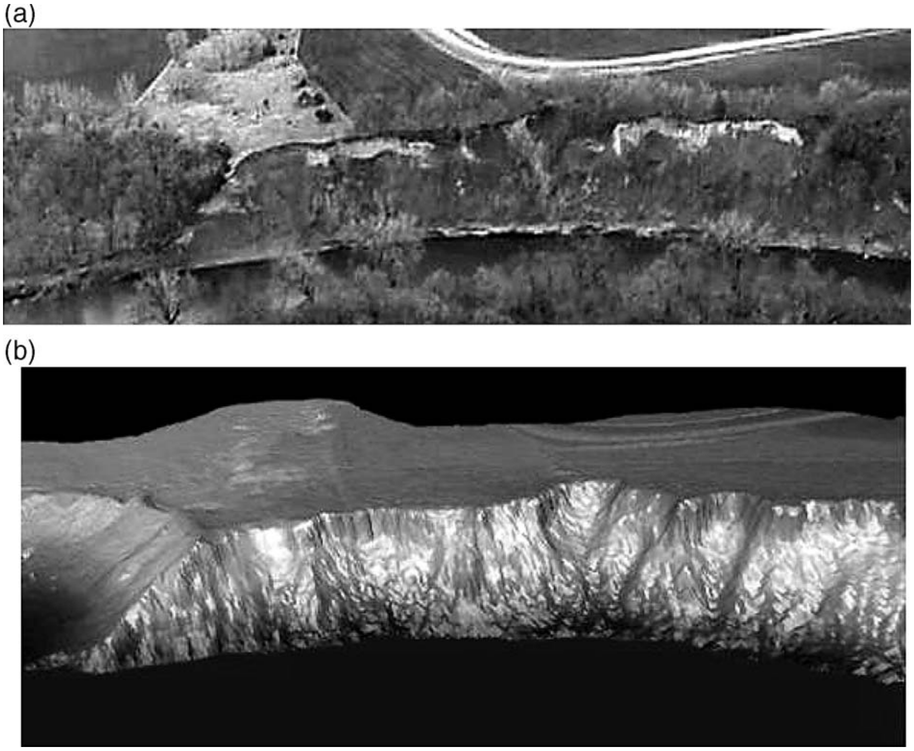

Fig. 2. (a) A severely eroded site along the Blue Earth River photographed at an oblique viewing angle from the air, and (b) rendered as a bare-earth elevation model from the LIDAR data. Vegetation was filtered and points gridded to a 1 m interval in the LIDAR image to create the model. Note gravel road passing through fallow field for scale in both figures.

textural analysis were used in conjunction with LIDAR determined volume change to derive mass wasting rates. All samples were analyzed for extractable phosphorus (Kuo, 1986) using 0.01 M $CaCl_2$, and total *P* via perchloric acid digestion (USEPA, 1981).

Elevation accuracy of both annual scans was determined by comparing the LIDAR scan elevations of bridges crossing the river to bridge elevations determined by real time kinematic (RTK) GPS survey in 2002. A total of 137 bridge reference points were collected on 5 highway bridges that crossed the scanned portion of the Blue Earth River. Accuracies of LIDAR scan elevations on the bridge surfaces were determined as the relative difference between a bridge reference point elevation and the nearest scan point elevation that fell on the surface.

The planimetric accuracy was determined by matching bridge edges in the 2001 scan to edges in the 2002 scan. Edges were determined by linear regression of scan line points (laser returns) that fell closest to, but still on, the bridge surface. The average distance between points on the best fit lines describing the bridge edges in 2001 and 2002 served as an estimate of planimetric shift. The maximum distances between control stations and bridges used as reference surfaces were 20.0 and 12.7 km in 2001 and 2002, respectively, less than the distance that would require ionospheric corrections (Shrestha et al., 1999).

2.3. Volume and mass change

Raw scanning laser data were differentially corrected and stripped of vegetation returns using a proprietary smoothing filter developed by the data provider, Aerotec LLC. Any last-return point greater than 1.5 m above ambient ground surface was considered a return from vegetation and was removed by the algorithm. Because data points were not uniformly distributed along the flight path due to mirror rotation and aircraft trajectory, they were gridded to uniform 1 m spacing in both X-and Y-directions before calculating the volume change. The resulting data product was an ordered set of 24 million and 30 million *X*, *Y*, *Z* coordinates for the 2001 and 2002 scans, respectively.

All data points below the 2001 high water mark (stream stage was higher in 2001 than in 2002 at time of scans) were eliminated from both data sets manually by digitizing and clipping to avoid confusing the difference in stream stage with changes in elevations due to erosion. Elimination of *X*,*Y* data points that were unique to one or the other uniformly gridded 1 m data sets produced two surface files (2001 data and 2002 data) with an identical number of *X*,*Y* coordinates over an identical geographic extent that differed only in the *Z* (elevation) dimension. The differences in *Z* values were determined for every vertex and summed. The sum was then multiplied by the spatial extent of the scans to arrive at an estimate of net volume change that occurred due to erosion or deposition between the two scans.

Mass wasting estimates were made by multipling average bulk density by the volume change determined from the LIDAR scans. Similarly, phosphorus load was derived by multiplying the concentration of extractable and total phosphorus in sediment samples by the mass of sediment that eroded into the river.

Sediment and *P* loads carried by the river were obtained from the Metropolitan Environmental Services (Heather Offerman, personal communication). These loads were measured using equal flow increment auto-sampling at a gauging station downstream from the scanned river reach.

3. Results

3.1. Properties of bank materials

Physical and chemical properties of bank materials were highly variable (Table 1) but strongly dependent on the type of fluvial, lacustrine or glacial deposit comprising the river bank. The bulk densities were higher, the textures more sandy and the phosphorus levels lower than agricultural surface soils in the area. In contrast, a surface soil (0–2 cm) collected from the summit of an eroding bank had an extractable *P* concentration 92% higher than the maximum bank extractable *P*, and 27% higher than the maximum bank total *P*.

3.2. Accuracy

The vertical accuracy of the RTK GPS reference points was determined to be between 1.22 cm and 1.83 cm by comparison with high accuracy bench marks. The strong correlation coefficient ($r^2 > 0.99$) between elevations of the bridge reference points and LIDAR scan points (Fig. 3) indicated a very close fit over an elevation range of tens of meters across approximately 16 km of horizontal survey

Table 1
Properties of upland surface soils and river bank materials collected from 12 samples at six river bank sites

		Bulk density (Mg/m^3)	Sand	Silt	Clay	Extractable *P*	Total *P*
			(%)			(mg/kg)	
Bank materials	Min	1.46	32.8	0.74	6.1	0	249
	Mean	1.83	55.7	27.3	20.1	0.08	392
	Max	2.13	92.4	41.6	29.3	0.25	452
Surface soil		1.25–1.45[a]	~10[a]	50–72[a]	18–40[a]	3.1	622

[a] Average physical properties from two common surface soils in the Blue Earth watershed (USDA, 1994). The soils are the Truman, and Waldorf series.

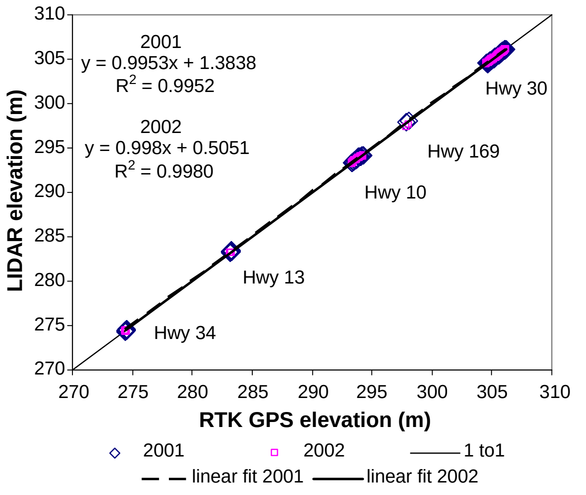

Fig. 3. Correspondence of bridge surface elevations obtained via RTK GPS survey on the ground versus elevations for the same surfaces determined by 2001 and 2002 LIDAR scans. Numbers refer to highway (Hwy) bridges used as reference surfaces. At 99% confidence level, *t*-test of slopes and intercepts indicate that slopes were not different from 1, but intercepts were different from 0 with *p*-values <0.002 and $p=0.000$ for both years for slope and intercept respectively.

distance. A hypothesis test of regression and slope coefficients indicated that slope was not significantly different from one while the intercepts were significantly different from zero, thus indicating the LIDAR elevations had high precision but a slight bias.

A closer inspection of vertical error made by subtracting scan elevations from RTK GPS elevations indicated the average error for the 2001 scan (2.5 cm) was less than that for the 2002 scan (8.8 cm) (Fig. 4 and Table 2), and the error distribution was somewhat normally distributed. Both scans under estimated elevations relative to RTK GPS bridge elevations and errors were statistically different from a mean of 0 cm.

The average relative planimetric difference between scans (Table 3) based on comparison of bridge edge positions in X,Y space was 1.5 m. This difference diminished to 0.83 m if Highway 10 and 34 were excluded due to the low number of laser returns used to define their edges. The number of laser returns used to define a bridge edge depends on bridge length, the orientation of scan lines relative to bridge edges, and the distance between laser returns in a scan line. This method does not provide a means to determine the absolute planimetric accuracy as was done for vertical error and thus should be considered qualitative.

3.3. Mass wasting and P inputs

A volume change of -281,454 m^3 was computed as the difference in elevations between the 2001 and 2002 LIDAR scans. This is equivalent to 512,247 t of sediment, 201 t total *P*, and 40 kg extractable *P* input to the river assuming a bulk density of 1.83 Mg/m^3, an average total *P* of 392 mg/kg in bank material, and an average extractable *P* of 0.08 mg/kg in bank material. More precisely these values represent net input of sediment, and total and extractable *P* from above the 2001 water line.

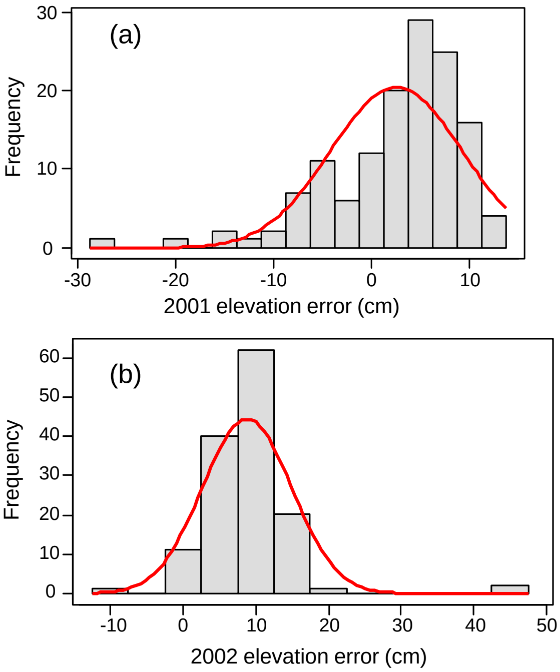

Fig. 4. Normal curves superimposed on distributions of elevation errors for LIDAR scans relative to 137 RTK GPS survey reference points collected on 5 bridges spanning the Blue Earth River. (a) 2001 with mean error 2.5 cm and 99% confidence interval (CI) {1.043, 4.027}, (b) 2002 with mean 8.8 cm and 99% CI {7.715, 9.793}. Lack of CI overlap indicates the error means are statistically different.

The mass of sediment and total *P* transported past the gauging station near the mouth of the Blue Earth River for the period between the two scans was 407,252 t and 982 t, respectively. However, not all of the eroded bank and bluff materials that made it to the river were transported past the gauging station within the year. For this reason a range of bank contributions to the suspended sediment load were calculated assuming different proportions of the river bank material may have been transported (Fig. 5). It was assumed that all of the *P* inputs could be transported because *P* was largely sorbed to smaller sized particles. Total *P* estimated

Table 2
Descriptive statistics for elevation error in the 2001 and 2002 LIDAR scans

	2001	2002
Mean (cm)	2.5	8.8
Median (cm)	4.2	8.9
Mode (cm)	4.2	10.7
Stdev (cm)	6.7	6.1
Variance(cm^2)	44.4	37.6
RMSE	6.7	6.1
99% Confidence interval for mean (cm)	{1.04–4.03}	{7.72–9.79}

Errors were computed as RTK GPS survey elevations minus elevations of the nearest LIDAR point on five highway bridges crossing the Blue Earth River. The total number of observations considered in this analysis was 137.

Table 3
Planimetric difference between bridge edges in 2001 and 2002 scans

Hwy	Bridge edge	2001 vs. 2002 average distance between best fit edges	# of points used to define edges		Direction of shift needed to correct	Coefficient of determination for best fit line through edge points (r^2)	
		(meters)	2001	2002		2001	2002
10	West	0.96	40	9	East	0.887	0.996
10	East	1.13	40	9	East	0.865	0.994
13	West	0.67	59	60	East	1.000	0.999
13	East	1.24	77	57	East	1.000	0.999
169	West	0.36	116	65	East	0.997	1.000
169	East	1.28	115	65	East	0.991	0.994
30	North	0.22	35	52	North	0.994	0.980
30	South	1.23	25	51	North	0.969	0.996
34	North	6.00	15	13	North	0.998	0.998
34	South	1.88	20	27	North	1.000	0.998
	Avg	1.50					

from LIDAR estimates of bank erosion represented 20% of the annual total P load measured at the gauge.

4. Discussion

4.1. Scanner accuracy

The vertical bias in the scans was most likely due to limitations in IMU angular measurement resolution and GPS positioning errors resulting from changing satellite configurations during the scan, or troposphere effects that degrade GPS signals (Shrestha et al., 1999; Wu & Yiu, 2001). Even though two additional ground control stations were used during the 2002 scan, the larger error in 2002 indicates that the error was due more to degraded GPS signal than lack of ground control or IMU resolution. In spite of the seemingly large error in 2002 relative to 2001, both scan errors are less than the specified noise level of the Topeye system (15 cm). The mean elevation error in this study was similar to mean elevation errors reported in the literature (Abdalati & Krabill, 1999; Favey et al., 1999; Huising & Gomes Pereira, 1998; Krabill et al., 1995).

Planimetric accuracy was more difficult to determine because bridge edges lay somewhere between the last point in a scan line that fell on the bridge, and the first that fell off the bridge. This distance was a function of point spacing on the ground and for these surveys ranged between 0.3 to 1 m depending on incident angle of LIDAR and degree of swath overlap. Scan orientation and distance between points in a scan line influenced the best fit line used to determine bridge edges. Edges invariably fell between points on scan lines, and if a point fell on an edge as indicated by multiple returns from a single point it was still difficult to determine exactly where the bridge edge was because laser point foot prints were approximately 16 cm in diameter. It was, however, reasonable to assume that this technique could detect gross errors in planimetric shift that might result in poor registration due to sub optimal satellite configuration or atmospheric effects that degrade the GPS signal.

Both vertical and horizontal bias corrections could be made to the LIDAR data to improve estimates of volume change over time. However, we feel that vertical bias would have to be evaluated on natural surfaces of varying slope and vegetation cover to have confidence that the bias reported here extends to such surfaces. Additionally, a good planimetric bias correction would require many ground control points exactly located along narrow bridge railings and on natural surfaces in order to more confidently determine absolute horizontal shift. Image-based break point alignment of stable surfaces could also be used to

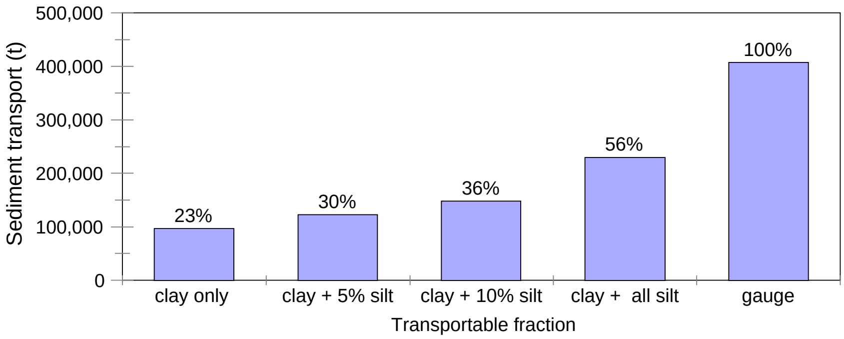

Fig. 5. Range in fraction of transported sediment that had its source in riverbank materials based on particle size of sediments added to the flow. Numbers above bars represent percentage of total load due to bank erosion for the given size fraction.

provide good planimetric alignment of independent LIDAR scans, but a purely image based approach should still be verified with ground control points.

4.2. Vegetation influence on mass wasting estimate

The influence of forest canopy on the bare earth digital elevation model was negligible, because the last pulse of most laser returns made it to the ground. This observation was apparent by noticing the small proportion of returns that were obviously reflections from canopy elements (apparent due to large change in vertical dimension over short horizontal distances) relative to the much larger number of points that represented reflections from the ground. The influence of low growing vegetation was difficult to determine. However, most of the actively eroding banks were devoid of vegetation that would cause interference, and banks with dense brush and grass cover were likely more stable and hence less likely to contribute to erosion. Forest canopy influence was minimized by making LIDAR scans within days of snowmelt prior to leaf out.

4.3. Mass wasting accuracy

No vertical or planimetric correction was applied to mass wasting calculations because error budgets were determined only for flat homogeneous bridge surfaces that were not representative of steep, rough and variably vegetated riverbanks. Furthermore, the detected errors were predominantly within the noise level of the measurement system, and were somewhat normally distributed. Additional research is needed to determine the cause of and solution for vertical and planimetric shift before application of correction factors.

While bias changes significantly due to time dependent variables associated with resolving GPS positions, it is less likely that variance, or system noise, will change significantly in future scans. One way to minimize the impact of variance on mass wasting estimates is to have a longer time period between scans. If erosion continues at a high rate the real topographic change will then be large relative to system noise, which will improve the capability of the airborne LIDAR scans to detect and measure changes.

In spite of the accuracy limitations noted in this study, there are no other methods for direct measurement of mass wasting that are as efficient. Surveying all of the banks included in the LIDAR scans for this study would be entirely impractical and unsafe using ground based methods. At a resolution similar to that obtained with the LIDAR system it took approximately 16 man hours in the field to survey 1000 m^2 of steep and rugged river bank with a total station. Cumulative flight time for the two annual scans along 56 km of river length was approximately 8 h over 2 days.

Although it was difficult to know what proportion of the bank material disaggregated and was transported it was assumed for discussion purposes that all the clay plus some of the silt fraction was entrained by flow. Following this assumption, between 23% to 56% of the suspended sediment may have had its source from bank materials. This of course depends on flow characteristics of the river and degree and strength of aggregation of eroded materials. A number of other factors influence this estimate of bank erosion and are discussed below.

4.4. Accuracy of sediment load

The accuracy of sediment and *P* transport measured at the gauging station was unclear. The water intake was located near shore in fast current about 0.46 m above the river bottom. Flow accuracy is also dependent on accuracy of rating curves that may change over time, and the accuracy and timing of stage measurements. This particular site has had a stable stage/discharge relationship largely due to bedrock control of channel morphology and had automated stage recording capability.

The dominant entrained particles were clay and silt fractions (WRC, 2004); however, it was difficult to precisely estimate what proportion of the mass wasting input to the river was suspended or bed load because of variations in particle size distribution, and aggregation of slumped materials, and stream power available for transport. Material not transported as suspended load was transported as bed load or settled out in low velocity areas of the stream and behind the dam. For this reason a range of possible sediment transport values are presented (23% to 56%) based on the assumption that all the clay and some or all of the silt was transported (Fig. 5). These estimates assume all slumped and eroded material that made its way into the river became dispersed and all clay was transportable. The veracity of this assumption improves over longer time scales as slumped aggregates disintegrate.

4.5. Unaccounted sources on net inputs

In spite of the relatively flat landscape outside the immediate river valley, there was potential for sediment and P input through surface inlets and tile lines. Another potential source was from eroding banks and bluffs upstream or downstream of the scanned section in 2001 and 2002. The contribution of bank materials below the dam (from downstream) was minimal as those banks were relatively stable and mostly composed of bedrock.

It is important to note that the river gauging station was located downstream from Rapidan Dam which impounds a reservoir nearly filled with sediment (emergent vegetation is visible approximately 50 m upstream of the dam), providing a settling reservoir for coarser particles. If significant settling occurred in the reservoir, then the estimate of bank contribution will be proportionately less, and hence even more conservative. Also, since the calculations explicitly excluded banks below the 2001 high water mark no accounting of erosion or deposition below that level was possible. Contribution from upstream banks was more likely, but was assumed to be small as the most actively eroding banks were contained within the scanned reach. Of 18 severely eroding sites along 157 km of the Blue Earth River, Bauer (1998) identified only two that were above or below the scanned section in this study.

4.6. Interpretation of mass wasting and P inputs

In this study, the highest mass wasting estimate ranged up to 56% of the transported load measured by a downstream gauging station, while the total P contribution was estimated at 20% from bank erosion. This does not imply that these percentages are directly attributable to bank erosion, which would require a rigorous accounting of bed and entrained loads bounding the scanned reach. Rather, these percentages are presented relative to the gauge load (1) to establish that the estimates using LIDAR are reasonable and (2) to further the discussion on how LIDAR could be useful in developing sediment budgets.

It is instructive to interpret the effect of bank erosion on sediment yield from the watershed. The annual load divided by watershed area represents the sediment yield. Based on the gauge data, the annual sediment and total P yields for the Blue Earth River watershed in 2001 were 647 kg/ha and 1.6 kg/ha, respectively. By subtracting the contribution of bank erosion from the total load the misappropriation of sediment yield to uplands that may have had its source in banks was determined to be between 149 and 362 kg/ha for sediment and 0.31 kg/ha for total P. Results such as these could have important bearing on land management at the watershed scale.

4.7. Role of LIDAR in soil erosion measurement

Due to weaknesses in current upland soil erosion models that fail to adequately account for gully erosion, bank erosion, sediment delivery from field to stream, and in stream sediment storage, alternative tools are needed for upland soil erosion measurement and prediction. With LIDAR technology, it is now possible that significant improvements could be made for large areas by developing sediment budgets that determine upland erosion by difference. This would represent a shift from empirically based upland erosion modeling to a physically based sediment budget approach (Trimble & Crosson, 2000). Airborne LIDAR could provide a unique role in erosion prediction technology for large areas and long time frames that will improve geomorphic and watershed scale erosion estimates that are strongly scale dependent (Osterkamp & Toy, 1997).

5. Conclusions

This study demonstrated the potential of LIDAR to partition non-point source sediment pollution from bank erosion. Using two scans made one year apart on the Blue Earth River in southern Minnesota estimated bank erosion inputs represented up to 56% and 20% of transported sediment and total P measured at a river gauging station. However, this does not mean all sloughed bank material made it to the gauging station in that year. These estimates are based on the volume change in river valley walls between 2001 and 2002 above the high waterline in 2001. Erosion or deposition below the high waterline could not be quantified because the laser wavelengths used are strongly absorbed by water.

Interpretation of mass wasting estimates derived from scanner data must be made in light of several factors that affect accuracy. These include the inherent errors in both laser altimetry measurements (vertical and planimetric shifts) and river gauging station measurements (accuracy in rating curve and stage measurements). Bias in scan elevations and planimetric accuracy may be corrected if systematic error can be separated from system noise. For the two annual scans used in this study the vertical error was within laser manufacturer specifications and no consistent bias was detected in planimetric shift. While there were sources of error in partitioning sediment using this method, it should be recognized that there are no conventional means of surveying at this level of accuracy for such extensive areas.

This study illustrated how scanning laser altimetry could be used in conjunction with river gauging station data to estimate the contribution of eroding bank materials to total suspended load. Operationally, resource managers at federal, state and local levels could use this technology to determine allocation of resources to projects with the greatest potential for pollution abatement. In addition, isolating stream bank inputs and upland contributions by difference with total sediment load can help determine effectiveness of upland soil erosion control efforts.

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